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Comparison of Synthetic Biogas Combustion Affected to Cellular Premixed Flames on Flat Burner

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Abstract

This study focused on the comparison of synthetic biogas combustion affected to cellular premixed flames on flat burner. As the variation of main composition of biogas such as methane (CH_4) and carbon dioxide (CO_2), the biogas produced from agricultural waste (57.93:45.07), food waste (73.39:26.61) and cow dung (85.13:14.87) were used to investigate for this study. Moreover, the lean combustion system was experimented on McKenna flat burner to reduce the greenhouse gases. The synthetic biogas on lean combustion system brought about the unstable behavior such as cellular flames due to intrinsic instability. The variation of equivalence ratio (0.65-1.0) and firing rate with 45 L/min of mixture flow rates were studied. Then the cell size, light emission detected by photodiode, power spectrum density analyzed by Fast Fourier and attractor constructed by Taken's embedding theorem, were analyzed. The results showed the cellular flame from agricultural waste, food waste and cow dung were found between Φ=0.75-1.00, Φ =0.70-0.90 and Φ =0.65-0.80, respectively. In addition, the blown off flames were also observed at $\Phi < 0.75$, $\Phi < 0.70$ and $\Phi < 0.65$ for agricultural waste, food waste and cow dung, respectively. As the decrease of equivalence ratio, the firing rate become lower, the reconstructed attractor was larger owing to diffusive-thermal instability. The results showed the variation of synthetic biogas of equivalence ratio and firing rate affected to cellular flames owing to the intrinsic instability. Moreover, it was concluded that small cell size, higher light emission and higher shaft peak frequency including narrow unstable range obtained in the combustion of biogas produced from cow dung, was more stable compared to biogas from agricultural waste and food waste sources.

Keywords: Cellular premixed flame, Synthetic biogas, Diffusive-thermal instability, Flat burner

1. Introduction

In the past, fossil fuel was used for the general combustion for industrial and heat process. Normally, carbon dioxide and nitrogen oxide were emitted and caused to climate change and greenhouse effects. Many researches were studied about new fuel to replace high carbon fuel such as liquefied petroleum gas (LPG), natural gas [1] and biogas [2]. This study focuses on the combustion of biogas because of wide applications in Thailand. In the past, the combustion of low-carbon fuel such as methane/air, butane/propane/air, and hydrogen/air [3-5] were investigated. In order to reduce the emission, the lean combustion was studied and found the effects of air/fuel ratio owing by thermal-diffusive instability [6-7]. In appearances of lean combustion were shown as lateral movement of flame front and cellular flame due to instability. Flame instability and flame phenomena were experimented and studied by Markstein [8-9]. The flame instability was observed by two main reasons as hydrodynamic instability and diffusive-thermal instability [10]. Hydrodynamic instability is caused by thermal expansion on flame front and heat loss. The diffusive-thermal instability was occurred from preferential diffusion between mass and heat and it can be identified destabilizing and stabilizing instabilities by Lewis number (Le<1.0) and Le>1.0, respectively [11-12]. In the past, hydrocarbon/ hydrogen/ carbon dioxide/ air premixed flames were studied with addition of methane into the process and cellular flame appeared by instability [13]. The study of shape and fluctuation of cellular premixed flames on lean combustion system of $CH_4/O_2/CO_2$ mixtures was studied to investigate the structure of cellular flame due to instability intensity [14]. Moreover, flame shape, fluctuation and cellular size of $CH_4/O_2/CO_2$ mixtures were obtained in lean combustion process [15]. In the previous study, the combustion of C_3H_8/C_4H_{10} flames on ceramic porous board was analyzed to obtain the cellular flame, size of cellular flame and light emission [16]. The effect of replacement of nitrogen with carbon has brought intrinsic instability and CO_2 increased, greater cell size, lower shape peak frequency of power spectral density and more complicated ring were observed [17].

Thus, this study focused on the comparison of synthetic biogas combustion affected to cellular premixed flames on flat burner. As the variation of main composition of biogas such as methane (CH_4) and carbon dioxide (CO_2), and wide application in power generation and heat process, thus it is interesting to investigate and compare the lean combustion of different composition biogas. The goal in this study is to investigate the characteristic of cellular flame such as cell size, light emission, power spectral density and reconstructed attractor with variation of equivalence ratio and firing rate to properly control the lean combustion system of biogas.

2. Experimental Apparatus

The experimental apparatus shown in Fig.1 is to study the phenomena of cellular flame. Following the experimental apparatus, Mckenna flat flame burner with 60 mm in diameter was applied. CH_4 and CO_2 mixtures flowed into digital mass flow controller (Azbil) from CH_4, CO_2 and air compressor to flat burner with fixed total gas flow rate as 45 L/min. In order to observe the cell size, cellular flame was taken by digital camera (Nikon D7100), measured the light emission by photodiode (HAMAMATSU, S1223-01) and transferred to data logger (HIOKI LR8431-20 Memory HI Logger). The measured intensity of light emission was normalized by Takens (1981) embedding theorem to create the reconstructed attractor that shown in Eq. (1).

$$V(t) = [y(t), y(t+\tau), y(t+2\tau), ..., y(t+(m-1)\tau)] \quad (1)$$

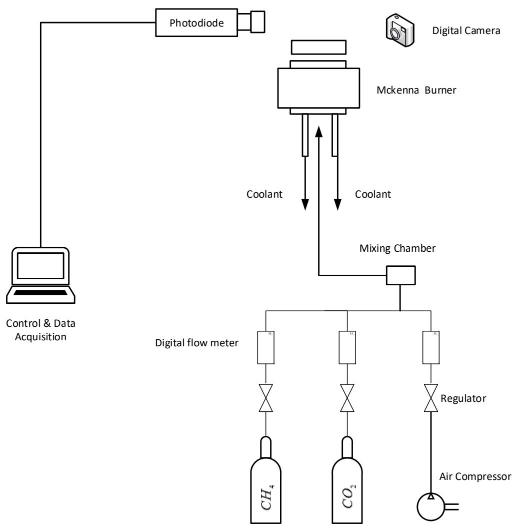

Fig.1 Experimental apparatus

3. Methodology

This experiment was studied with three variations of biogas compositions as agricultural waste, food waste and cow dung. The flow rate was fixed at 45 L/min and followed by chemical reaction as in Eq.(2)-(4). In this experiment, the variation of equivalence ratio and variation of firing rate were studied and followed by Table. 2-4.

$$0.5793CH_4 + 0.4507CO_2 + 1.1286(O_2 + 3.76N_2) \rightarrow CO_2 + 1.1586H_2O + 4.243N_2 \quad (2)$$

$$0.7339CH_4 + 0.2661CO_2 + 1.4678(O_2 + 3.76N_2) \rightarrow CO_2 + 1.4678H_2O + 5.518N_2 \quad (3)$$

$$0.8513CH_4 + 0.1487CO_2 + 1.7026(O_2 + 3.76N_2) \rightarrow CO_2 + 1.7026H_2O + 6.401N_2 \quad (4)$$

Table. 1 Biogas compositions

Biogas resources	CH_4 [%]	CO_2[%]
Agricultural waste	57.93	45.07
Food waste	73.39	26.61
Cow dung	85.13	14.87

Table. 2 The variations of synthetic biogas produced from agricultural waste.

Φ	Composition (%)		Gas flow rate(L/min)			Firing rate (kW)
	CH_4	CO_2	CH_4	CO_2	air	
0.62			2.5	2.1	40.4	2.54
0.65			2.6	2.2	40.2	2.65
0.70			2.8	2.3	39.9	2.80
0.75	0.5493	0.4507	3.0	2.5	39.5	3.03
0.80			3.2	2.6	39.2	3.17
0.85			3.3	2.7	39.0	3.29

Table. 3 The variations of synthetic biogas produced from food waste.

Φ	Composition (%)		Gas flow rate (L/min)			Firing rate (kW)
	CH_4	CO_2	CH_4	CO_2	air	
0.75			3.1	1.1	40.8	2.51
0.79			3.2	1.2	40.6	2.66
0.80	0.7339	0.2661	3.3	1.2	40.5	2.70
0.845			3.4	1.2	40.4	2.74
0.85			3.5	1.3	40.2	2.90

3.1 Cell size analysis

The definition of cell size is the distance between top of cellular flame front as shown in Fig. 2. The study was investigated to illustrate the instability intensity such a cell size of cellular flame which can be described by Eq (5).

Table. 4 The variations of synthetic biogas produced from cow dung.

Φ	Composition (%)		Gas flow rate (L/min)			Firing rate (kW)
	CH_4	CO_2	CH_4	CO_2	air	
0.75			3.1	0.5	41.4	2.12
0.80			3.3	0.6	41.1	2.35
0.85			3.5	0.6	40.9	2.44
0.86			3.6	0.6	40.8	2.49
0.90	0.8513	0.1487	3.7	0.6	40.7	2.54
0.91			3.7	0.7	40.6	2.67
0.95			3.9	0.7	40.4	2.76
0.975			4.0	0.7	40.3	2.81

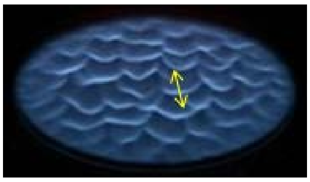

Fig.2. Definition of cell size.

$$X_a = X_p(D_a/D_p) \qquad (5)$$

X_a = Actual Cell size
X_p = Cell size from illustrate
D_a = Actual Burner diameter
D_p = Burner diameter from illustrate

3.2 Power Spectral Density

The light emission detected from photo-diode was analyzed by Fast Fourier Transform (FFT) to obtain the shaft peak frequency (f_1). Moreover, the shaft peak frequency had the relationship with time delay (τ) as shown in Eq. (6).

$$\tau = \frac{2}{f1} \qquad (6)$$

3.3 Reconstructed Attractor analysis

The reconstructed attractor was analyzed by Takens' embedding theorem with time delay obtained from power spectral density. The embedding, m=3 was set in vector $\vec{V}(t)$ followed by Eq. (7) to create attractor. The reconstructed attractor was analyzed to investigate the effects on biogas combustion flames induced by variation of resources.

$$\vec{V}(t) = [y(t), y(t+\tau), y(t+2\tau), \cdots, y(t+(m-1)\tau)] \qquad (7)$$

4. Results and Discussion

This study, the equivalence ratio and firing rate in biogas combustion from agricultural waste, food waste and cow dung, were investigated. The main compositions of biogas are CH_4 and CO_2 which is different in above three biogas resources. The combustion of biogas was experimented and the cell size, power spectrum density and reconstructed attractor were obtained. The results of variation of equivalence ratio were obtained in the range of cellular flame in each cases. It was shown in Table. 5. The combustion of biogas from agricultural waste was found cellular flame in range between Φ = 0.75-1.00 and blow off was occurred when Φ < 0.75, from food waste was found cellular flame in range between Φ = 0.70-0.90 and blow off was occurred when Φ < 0.70 and from cow dung were found cellular flame in range between Φ = 0.65-0.80 and blow off was occurred when Φ < 0.65.

Table. 5 Ranges of cellular flame in each sources.

Biogas source	CH_4[%]	O_2[%]	Cellular Flame
Agricultural waste	57.93	45.07	Φ =0.75-1.00
Food waste	73.39	26.61	Φ =0.70-0.90
Cow dung	85.13	14.87	Φ =0.65-0.80

4.1 Cell size of cellular flame

When the equivalence ratio increased, the cell size was lower due to increase of stability. Figure 3 shows the equivalence ratio decreases from 0.85 to 0.75, the cell sizes were increased from 9.20 mm to 10.8 mm for agricultural waste source, increased from 5.84 mm to 8.86 mm for food waste source and increased from 4.95 mm to 7.28 mm for cow dung source. As the results, agricultural waste source was more unstable than food waste and cow dung in respectively due to increase of stability induced by CH_4 concentration.

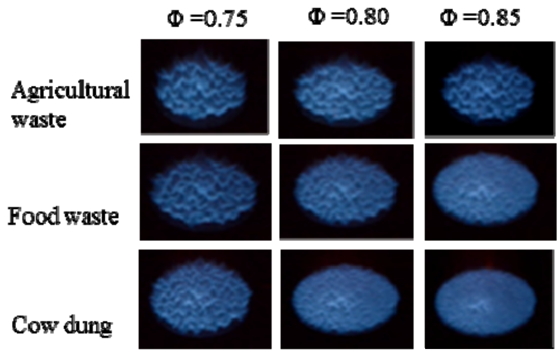

Fig. 3. The cell size with variation of equvalence ratio for agricultural waste, food waste and cow dung.

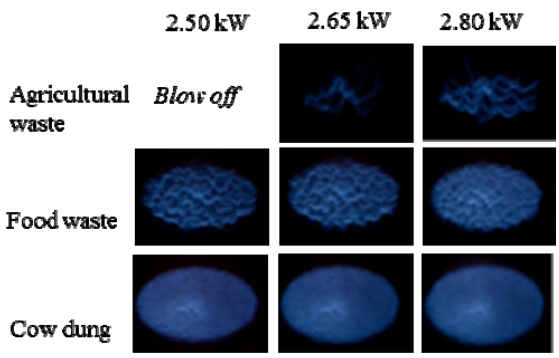

Fig. 4. The cell size with variation of firing rate for agricultural waste, food waste and cow dung.

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Moreover, at the variation of firing rate from 2.50 kW until 2.80 kW then the cell size was smaller. Figure 3 shows that the decrease of firing rate affected to increase of cell size of biogas from food waste as 6.45 mm to 8.86 mm. However, during firing rate variation, cell size from cow dung source was not changed and the blow-off flame was occurred for agricultural waste source.

4.2 Power spectral density

Figure 5-6 show that the equivalence ratio of biogas combustion from agricultural waste source increases, the the sharp peak frequency from power spectrum density was higher due to increase of stability. At the same equivalence ratio, Φ =0.80, the sharp peak frequency from power spectral density from cow dung source is higher compared to agricultural waste and food waste sources due to stability intensity as shown in Fig. 7-8.

For food waste source, when the firing rate decreased from 2.80 kW until 2.50 kW then the sharp peak frequency from power spectral density was lowered as shown in Fig. 9-10. The results also found that at the firing rate 2.80 kW in Fig.11, the highest sharp peak frequency of power spectral density was obtained from cow dung source due to the increase of energy.

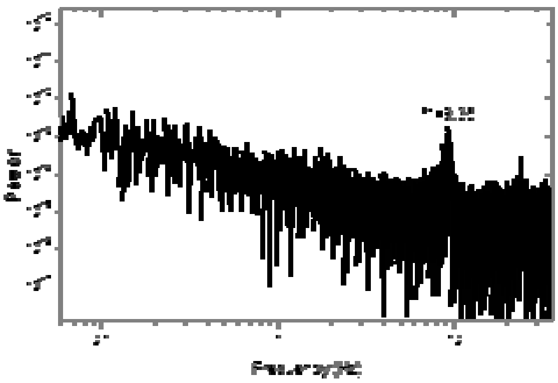

Fig. 5 Power spectral density of agricultural waste source at Φ =0.75.

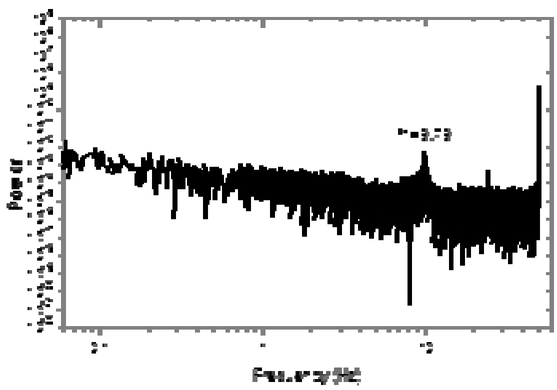

Fig. 6 Power spectral density of agricultural waste source at Φ =0.80.

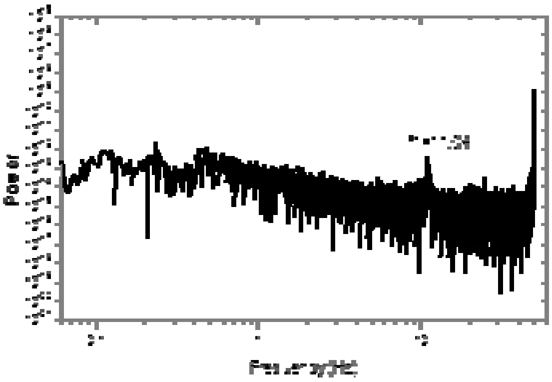

Fig. 7 Power spectral density of food waste source at Φ =0.80.

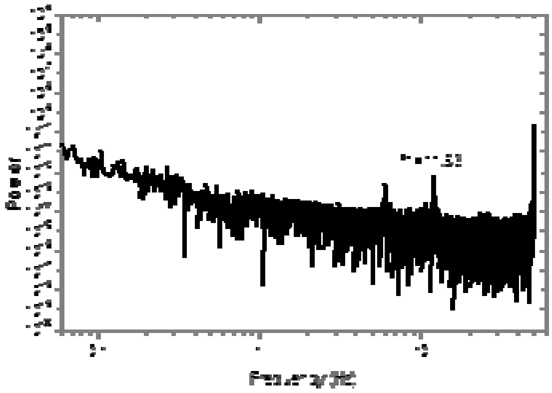

Fig. 8 Power spectral density of cow dung source at Φ =0.80.

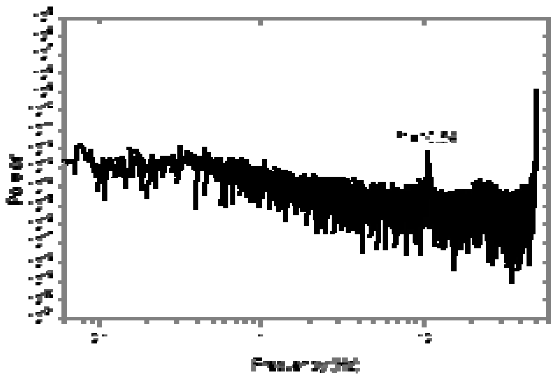

Fig. 9 Power spectral density of food waste source at F.R =2.65 kW.

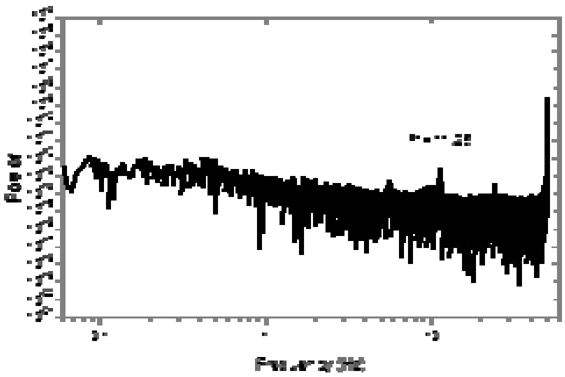

Fig. 10 Power spectral density of food waste source at FR =2.80 kW.

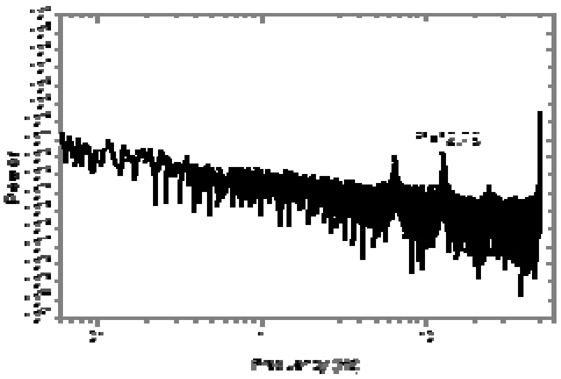

Fig. 11 Power spectral density of cow dung source at F.R. =2.80 kW.

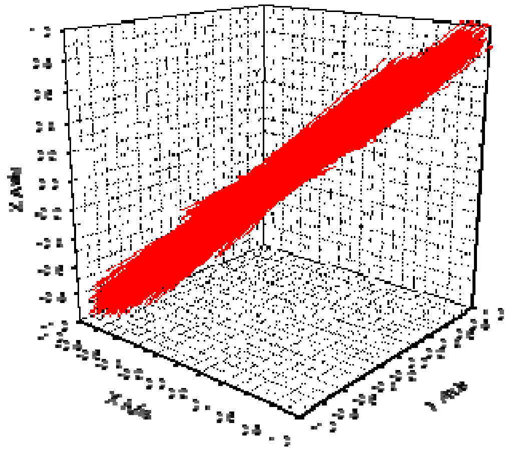

Fig. 13 Reconstructed attractor of agricultural waste at Φ=0.80.

4.3. Reconstructed attractor

As the previous results, the shaft peak frequency was calculated to obtain the time-delay to create the reconstructed attractor in three-dimension. Fig. 12-13 show that the equivalence ratio of biogas combustion from agricultural waste source increases, the size of reconstructed attractor becomes smaller due to decrease of instability. At the same equivalence ratio, Φ = 0.80, the attractor from cow dung source is the greatest compared to agricultural waste and food waste sources due to stability intensity as shown in Fig. 13-15.

For food waste source, when the firing rate decreased from 2.80 kW to 2.50 kW, then the reconstructed attractor was greater as illustrated in Fig. 16-17. Moreover, Fig. 18 shows the firing rate of 2.80 kW, the smallest attractor was obtained from cow dung source due to the increase of energy induced higher stability.

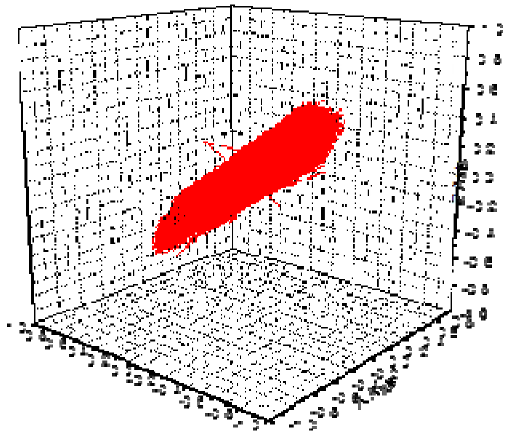

Fig. 14 Reconstructed attractor of food waste source at Φ =0.80.

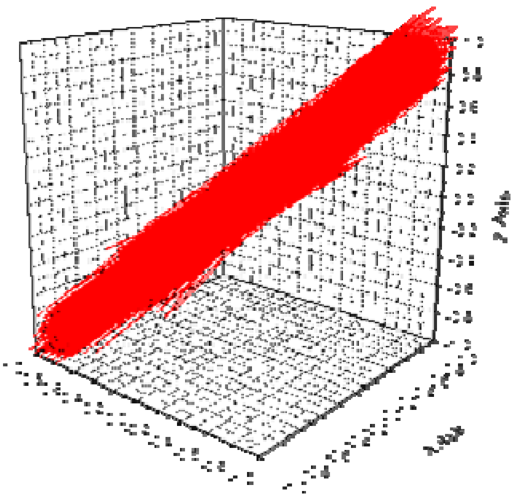

Fig. 12 Reconstructed attractor of agricultural waste at Φ=0.75.

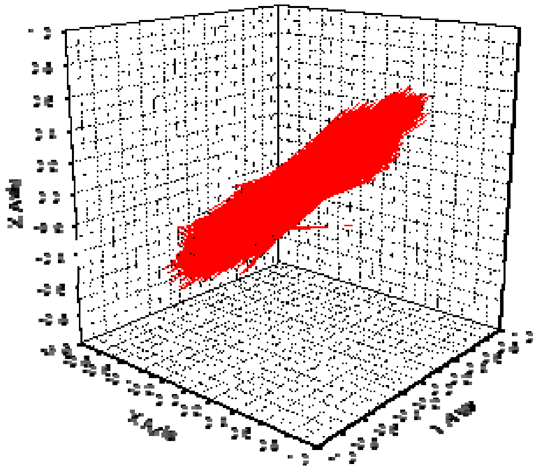

Fig. 15 Reconstructed attractor of cow dung source at Φ =0.80.

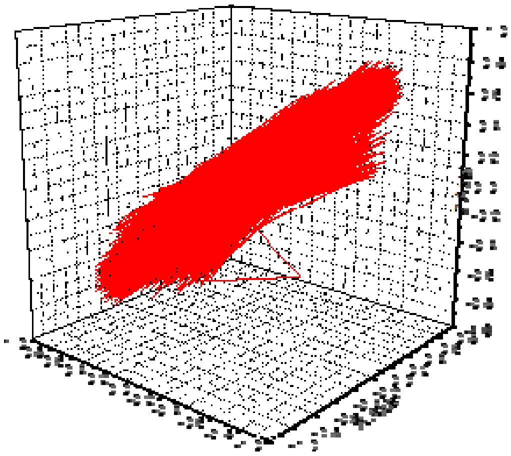

Fig. 16 Reconstructed attractor of food waste at F.R =2.50 kW.

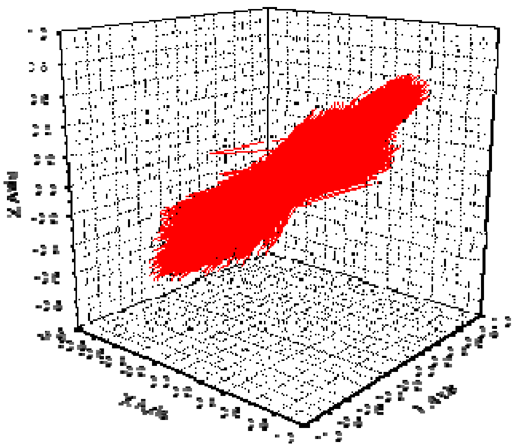

Fig. 17 Reconstructed attractor of food waste at F.R =2.65 kW.

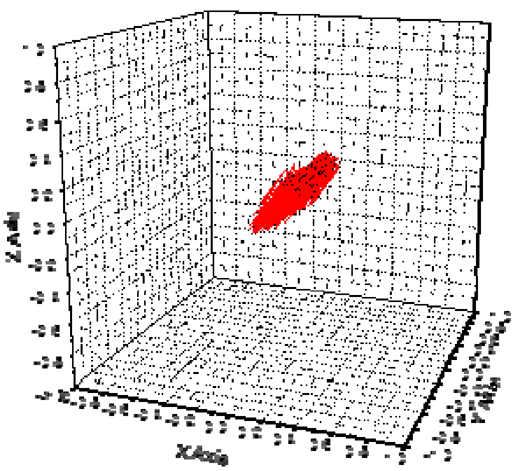

Fig. 18 Reconstructed attractor of cow dung at F.R =2.80 kW.

5. Conclusions

This study focused on the variation of main composition of biogas such as methane (CH_4) and carbon dioxide (CO_2) which produced from agricultural waste (57.93:45.07), food waste (73.39:26.61) and cow dung (85.13:14.87). The cell size, light emission detected by photodiode, power spectrum density analyzed by Fast Fourier and attractor constructed by Taken's embedding theorem were analyzed. The results showed that agricultural waste, food waste and cow dung yield the cellular flame between Φ=0.75-1.00, Φ =0.70-0.90 and Φ =0.65-0.80, respectively. In addition, the blown off flames were also observed at $\Phi < 0.75$, $\Phi < 0.70$ and $\Phi < 0.65$ for agricultural waste, food waste and cow dung, serially. As the decrease of equivalence ratio, the firing rate become lower, the reconstructed attractor was larger owing to diffusive-thermal instability. The results showed the variation of synthetic biogas of equivalence ratio and firing rate affected to cellular flames owing to the intrinsic instability. Moreover, it was concluded that small cell size, higher light emission and higher shaft peak frequency including narrow unstable range obtained by the combustion of biogas produced from cow dung was more stable compared to biogas from agricultural waste and food waste sources.

6. Acknowledgement

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